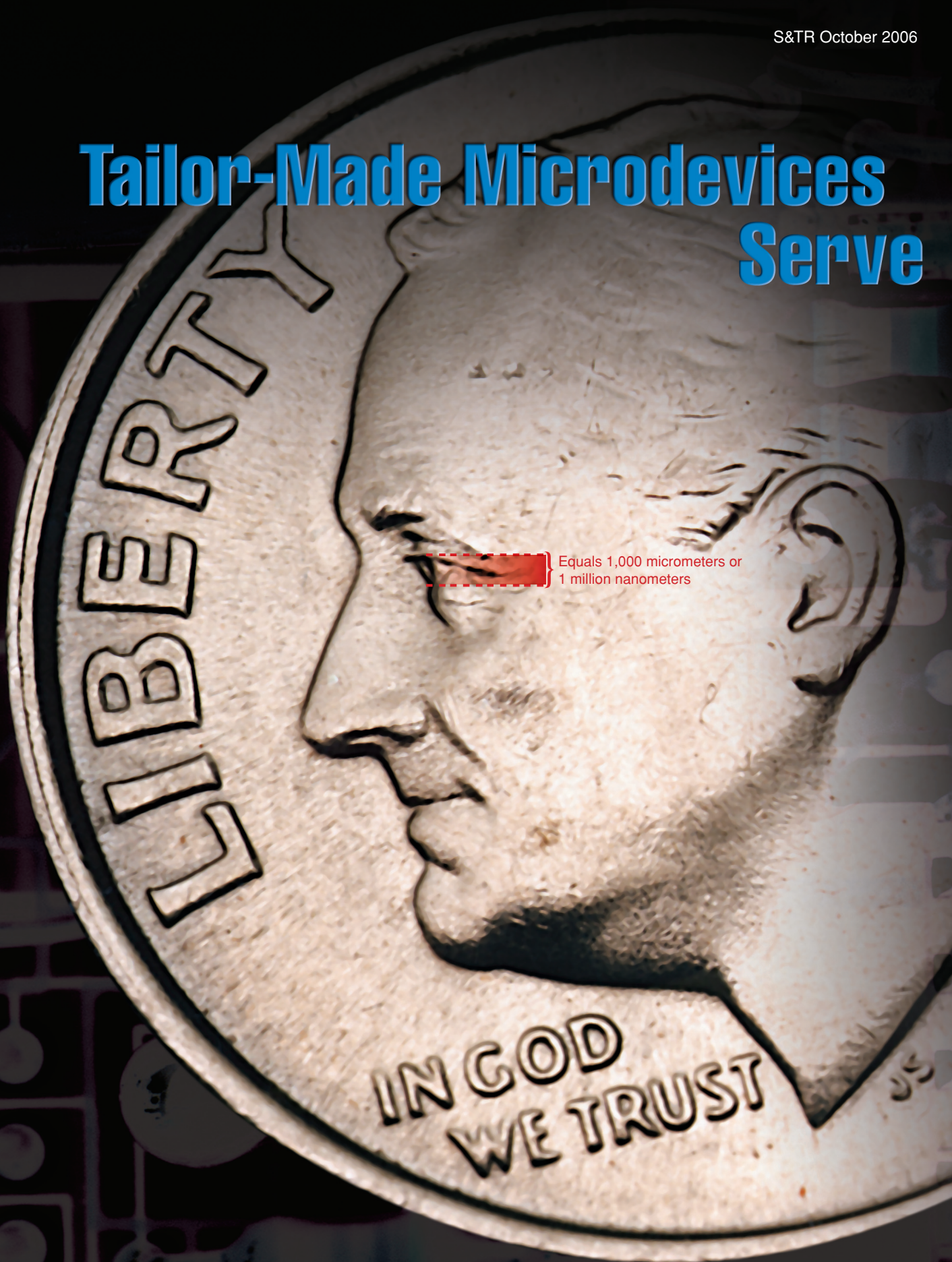


Tailor-Made Microdevices Serve



Big Needs

Livermore engineers invent and fabricate micrometer- and nanometer-scale devices for national security.

AT one time or another, almost everyone wishes for a custom-made gadget to perform a specific task. Talented engineers often find a way to transform those ideas into workable devices. At Livermore's Center for Micro- and Nanotechnology (CMNT), fulfilling special requests has an added challenge because researchers must focus on the very tiny. "CMNT engineers, scientists, and technicians develop technologies with critical dimensions that are only a few nanometers to micrometers in size," says Mike Pocha, the center's chief engineer. "Much of the Laboratory's research for its national security missions requires unique devices not available commercially, so we invent and manufacture them here at Livermore."

The tailor-made components designed at CMNT range from highly integrated biomicrosystems for sensors and medical devices to photonic microsystems for high-speed signal and data acquisition, microelectromechanical systems (MEMS) for sensing and actuation, and micrometer- and nanometer-scale energy systems for miniature power supplies. A measure of the center's success is the number of patents issued to its staff members. In the past two years, more than 20 percent of the Laboratory's patented technologies were developed at CMNT.

Originally called the Center for Microtechnology, the center was formed

in the 1980s as part of Livermore's Engineering Directorate. Its early efforts focused on high-speed diagnostics and radiation detectors for underground nuclear testing. CMNT researchers were among the first to combine micro-optical devices, such as laser diodes and guided-wave photonics, with microelectronics, increasing processing speeds by several

orders of magnitude compared with those of electronic devices.

In 2000, the center changed its name in recognition of the push for technologies with ever-smaller components. Most devices are designed to meet specific programmatic needs, such as targets for experiments on the National Ignition Facility (NIF). But the staff often finds that



At the Center for Micro- and Nanotechnology, researchers develop micrometer- and nanometer-size devices and systems in support of the Laboratory's national security missions. The critical dimensions of these technologies are much smaller than the highlighted area of the dime shown on p. 18.

a new tool has commercial applications as well. “For example, our engineers invented components for a MEMS-based contact stress sensor designed as a flight-test diagnostic,” says Pocha, who has worked at the center since it was formed. “We also adapted the stress sensor for biomedical research to measure the contact stress in, say, a knee joint or an artificial limb.” (See *S&TR*, April 2006, pp. 4–9.)

As with many of the center’s developments, the stress sensor resulted from the ingenuity of young researchers with a fresh approach for solving a complicated problem. CMNT director Anantha Krishnan says, “A large part of our strategy is hiring young engineers and scientists who bring in new ideas and skills to help achieve the long-range project and mission goals being pursued by senior researchers.”

Ring in the Light

For example, consider engineer John Heebner. Before he joined the Laboratory in 2003, Heebner completed his Ph.D.

dissertation on the use of microresonators to enhance optical propagation in waveguides. He now focuses on devising optical-based devices to replace traditional electronic components and systems, such as switches, transistors, oscilloscopes, and streak cameras.

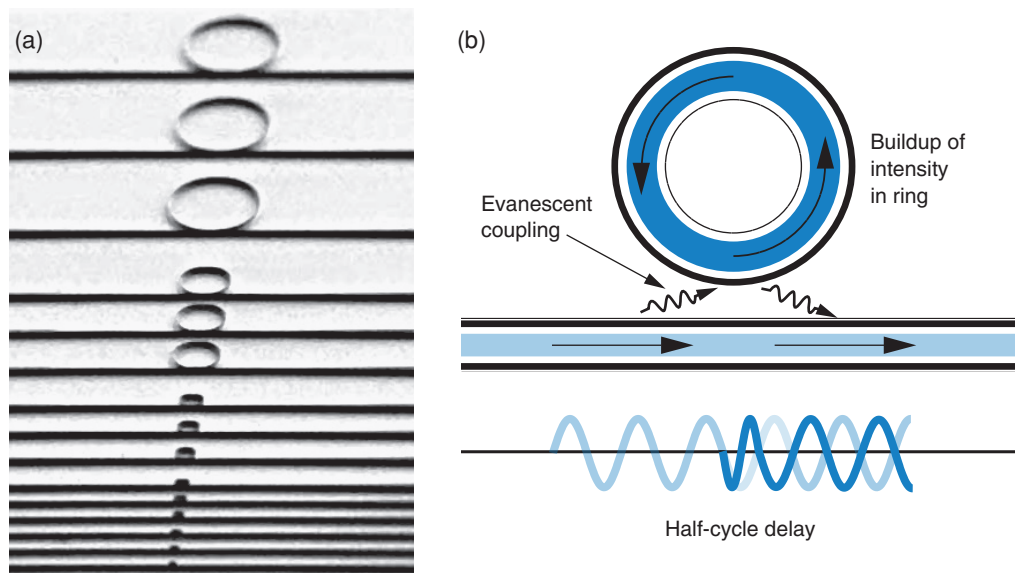
Optical or photonic systems rely on photons rather than electrons to carry signals. Photons transfer information 10 to 100 times faster than electrons while maintaining better signal integrity. Light is also more secure from interference. These characteristics make optical-based systems ideal for long-distance communications.

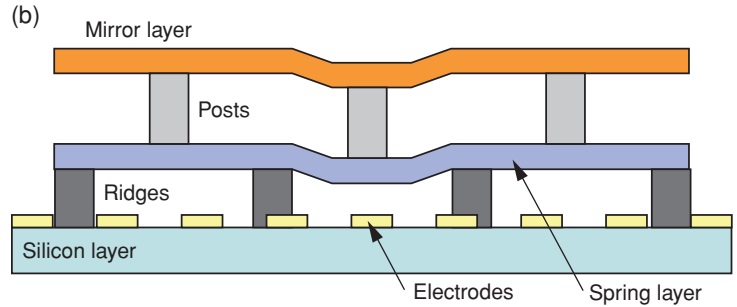
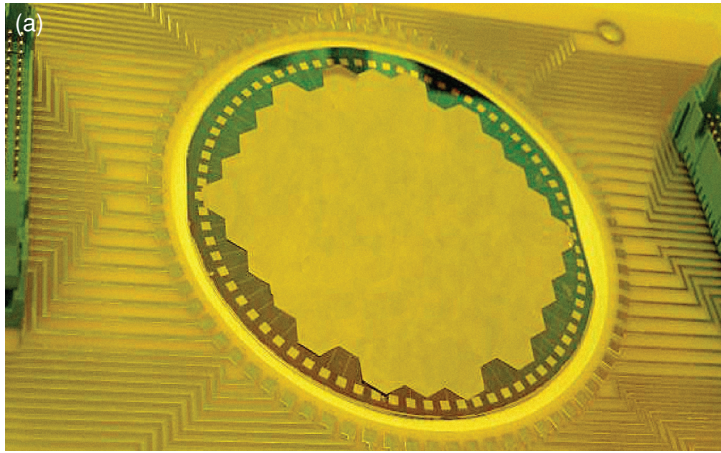
However, technology has not been sufficiently developed to enable all-optical signal processing, in which photons operate on or reroute other information-carrying photons. The problem is that photons do not interact with each other nearly as readily as electrons do. Therefore, most modern communication architectures use hybrid systems in which electronics process the photons and optics merely channel them.

According to Heebner, a potential technology for unlocking the promise of all-optical systems is microresonators. “In any optical material, at a sufficiently high intensity, one light beam can control a second beam by altering the refractive index it experiences,” he says. A material’s refractive index is a measure of the slow-down factor for light propagating inside it. Delaying the propagation time by a half-cycle is enough to enable an optical switch or gate. Unfortunately, these effects are very weak, typically requiring long devices or impractically high intensity levels.

Microresonators could be an effective solution to this problem. Says Heebner, “Microresonators strengthen the interactions of photons in a compact device.” One type of microresonator consists of a ring structure made with a semiconductor material such as silicon or gallium arsenide. The microring confines light so it circulates in tight bends, enhancing both the interaction time and the intensity level of electromagnetic waves at

(a) Microring resonators with diameters that vary from 50 to 5 micrometers are etched in aluminum gallium arsenide. The waveguide cross sections that channel the light are smaller than 1 square micrometer, or 100 times smaller than conventional optical fibers. (b) In a microring resonator, incident light propagating in a waveguide evanescently couples into the ring, traversing the ring for many trips while building up its circulating intensity. The combined action of these effects can delay the propagation by a half-cycle at a significantly reduced intensity threshold. Compact all-optical switches can be built by using this effect to augment the constructive and destructive interference.





(a) This 76-pixel deformable mirror made from nanolaminate foil provides a lightweight alternative to the glass mirrors typically used in telescopes.
(b) When electrodes stimulate the spring layer, it deforms and adjusts the mirror pixels.

specific resonant frequencies. With these enhancements, two pulses of light interact with each other 1,000 times more strongly while preserving the high speed.

Heebner leads a CMNT team that is investigating whether arrays of microring resonators can be used to design all-optical systems. The concept of a ring resonator has been around for some time, but limitations in existing optical materials and fabrication techniques have restricted

the development of the arrays. Part of the Livermore project is to determine what improvements in fabrication techniques are needed to enable an all-optical system. The ring resonators are also being used in optical filtering and sensing applications.

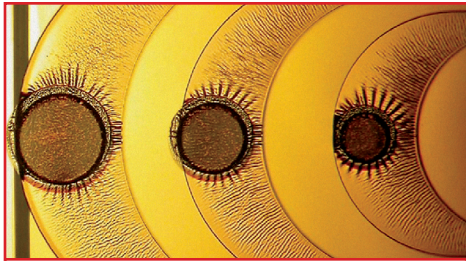
Heebner is also working with a team from the NIF Programs and Defense and Nuclear Technologies directorates to design an all-optical oscilloscope or streak camera. These traditionally electron-based recording instruments are a staple of experimental facilities that measure high-speed events. The optical device being designed by Heebner's team uses an intense, auxiliary pulse of light to instantly create a microprism that rapidly

deflects a primary light beam. The team's goal is to provide a faster alternative to conventional recording instruments by implementing novel all-optical recording technologies.

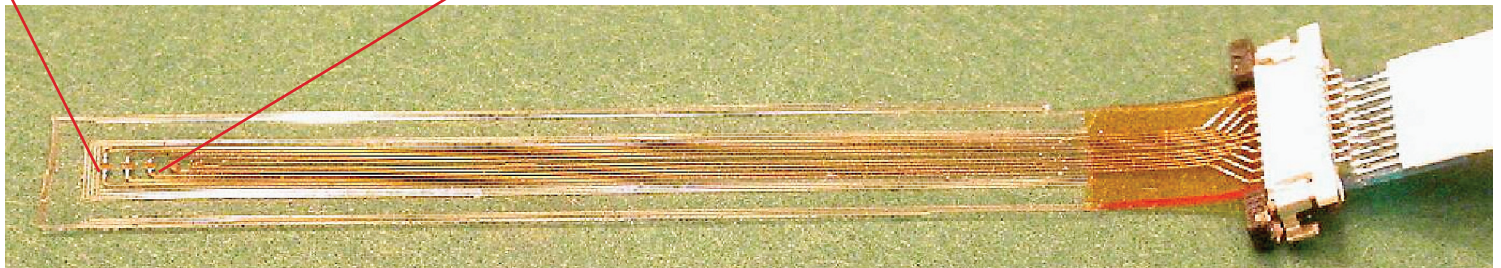
Foils Replace Glass Mirrors

CMNT also applies its optics expertise to research in MEMS-based adaptive optics (AO) for use in telescopes. (See *S&TR*, June 2006, pp. 14–21.) These systems adjust for the distortions of light caused by atmospheric aberrations, so observers have a clearer view of objects in space.

The deformable mirrors on AO systems are traditionally made of etched silicon



Conductive lead and metal electrodes are embedded in a polymer substrate for the retinal prosthesis. A close-up shows the electrode region of the retinal implant.



glass. MEMS actuators adjust the shape of each pixel on a mirror hundreds of times per second. The largest AO systems built to date have arrays of mirrors with no more than 1,000 pixels. Tens of thousands of pixels are needed for AO systems on space-based telescopes. Newer terrestrial systems, such as the proposed Thirty Meter Telescope, will require thousands of pixels. But mirror size is limited by the weight of glass and the fabrication techniques available.

To solve this problem, mechanical engineer Alex Papavasiliou worked with colleagues in the Chemistry, Materials, and Life Sciences (CMLS) and Physics and Advanced Technologies (PAT) directorates to develop lightweight deformable mirrors using nanolaminate foils instead of glass for the mirror surface. Nanolaminate foils are composed of thousands of alternating

layers of copper and zirconium, each of which are a few nanometers thick. Nanostructuring limits the material's grain size, giving the foil the strength and toughness to handle bonding during fabrication and the flexibility to withstand rigorous deformations as the individual pixels adjust many times.

Papavasiliou also devised a microfabrication technique that creates the actuator for nanolaminate foils. Mirrors can be fabricated in batches rather than individually by hand as in the conventional process. In addition, the design can be scaled from a few centimeters to 1 meter or larger.

Restoring Sight

Many experienced engineers join the Laboratory because of its broad scope of research. CMNT engineer

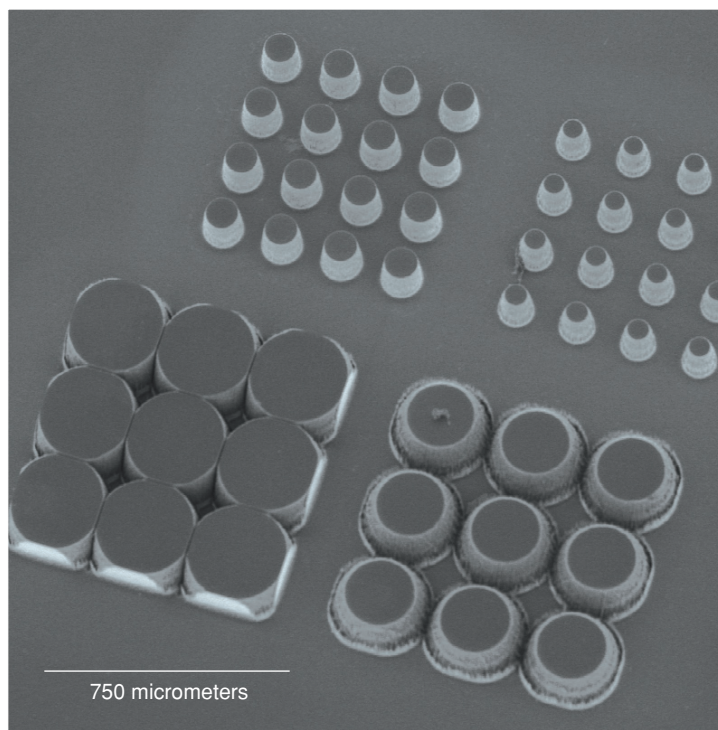
Satinderpall Pannu previously worked at Onix Microsystems, Inc., developing micromirrors to be used in optical switches for telecommunications. In his current assignment at Livermore, Pannu leads a multi-institutional effort funded by the Department of Energy's Office of Science to develop a prosthesis for treating retinal diseases such as macular degeneration and retinitis pigmentosa. (See *S&TR*, November 2003, pp. 11–13.)

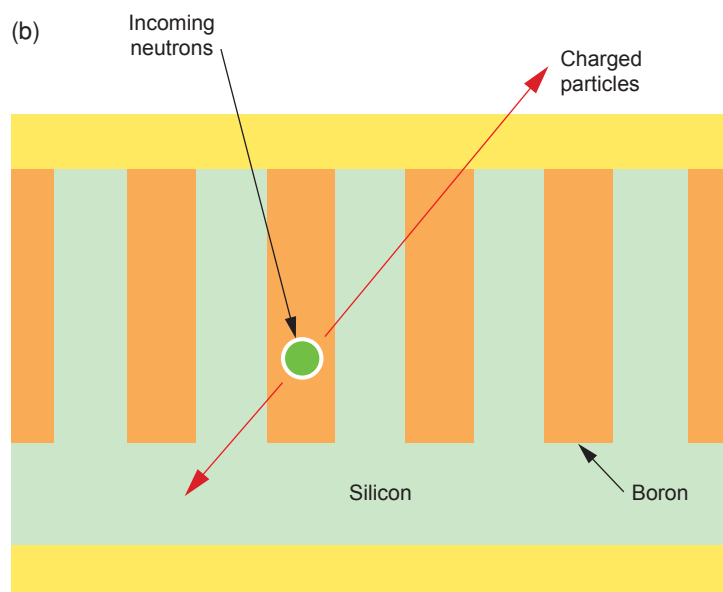
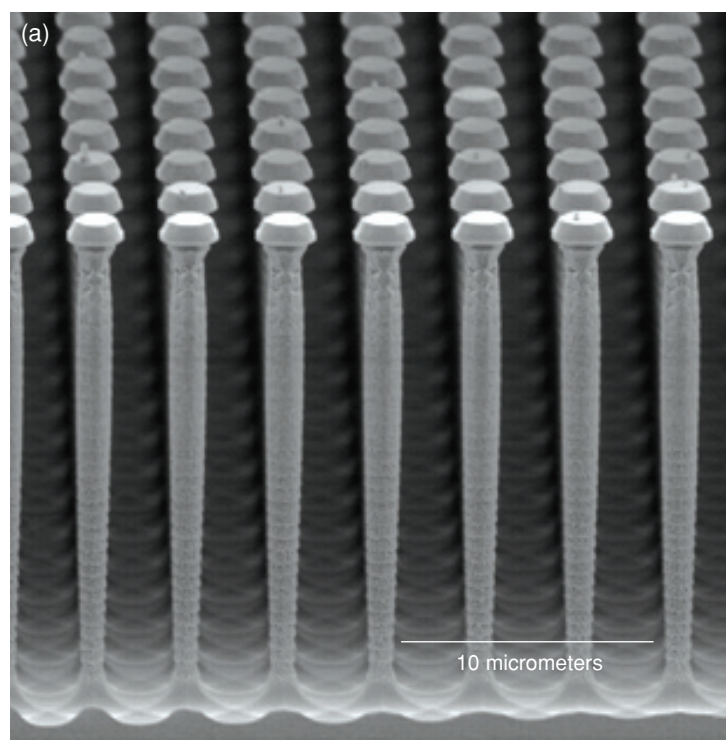
The retinal prosthesis consists of a microelectrode array embedded in a polymer substrate. CMNT is fabricating a 240-electrode array that will serve as the interface between an electronic imaging system and the retinal tissue. The array, which sits on top of the retina, uses electrical impulses to stimulate the retinal tissue. Therefore, the device must be very small and compatible with biological tissue.

Researchers at Argonne National Laboratory are using an ultrathin coating called ultrananocrystalline diamond, which they developed for use on microchips, to package a complementary metal oxide semiconductor chip onto the electrode. North Carolina State University is modeling the prosthesis, and Los Alamos National Laboratory is conducting experiments to ensure that all components are thermally safe to the retina. Elias Greenbaum tests the implants at Oak Ridge National Laboratory to determine their biocompatibility.

Wen Tai Liu, an engineer at the University of California at Santa Cruz, designed wireless radio-frequency communication to connect the implant to external equipment. This innovative system includes a video camera that sits on eyeglasses and transmits images to the implant. Mark Humayan, a retinal surgeon and biomedical engineer at the University of Southern California's Doheny Eye

Grayscale lithography can be used to fabricate microdevices with various three-dimensional shapes, such as the rounded and tapered lens-type features shown here.





(a) The etched silicon pillars used in the pillar detector are 20 micrometers in height and spaced about 2 micrometers apart. (b) In a thermal neutron detector, incoming neutrons interact with the pillars within a semiconductor matrix.

Institute, is developing procedures to implant the device.

The team plans to test a prototype device in June 2007. If additional funding can be acquired, they want to expand the array to 1,000 electrodes.

Etching in Three Dimensions

One technology that may benefit future versions of the retinal prosthesis is grayscale lithography—a technique for creating a three-dimensional (3D) microstructure. Conventional photolithography produces a two-dimensional (2D) structure from a silicon wafer. The wafer is coated with a light-sensitive material called a photoresist and patterned with a photomask. When ultraviolet light is sent through the mask, it exposes parts of the wafer. Chemical etching is then used to reveal the pattern created by the photomask.

Light exposure in the 2D process is all or nothing, so photoresist features have a uniform height. Grayscale lithography allows researchers to adjust the light's intensity, resulting in 3D photoresist profiles with a variety of shapes. After chemical etching, the profiles can be transferred to a substrate. CMNT engineer Chris Spadaccini is exploring the technique's potential for devices such as micro-optics and targets for physics experiments as well as for other types of 3D structures such as the retinal prosthesis. Spadaccini says, "Grayscale lithography opens up many possibilities in microfabrication because we don't have to design in 2D."

Spadaccini joined the Laboratory in 2004 to extend his experience from aerospace propulsion and power. He is also using CMNT's capabilities to develop nanostructured thermoelectric devices

that can work as power sources in sensors and as coolers in biodetection systems. Thermoelectric devices convert thermal energy into electrical energy to generate power. They also can operate in reverse, using electrical energy to move heat for cooling. These systems have a longer lifespan than conventional electrical power generation and cooling methods, they produce no gaseous emissions, and they are highly reliable. However, they typically have low efficiency, which limits their use in field applications.

Spadaccini and his collaborators in the CMLS and PAT directorates want to solve this problem so thermoelectric devices can be adapted for homeland security applications. The team's concept is to design composite material of carbon nanotubes and polymers that will improve electron transport while simultaneously

blocking phonon transport. “Research shows that carbon nanotubes dispersed in polymer matrices form highly conductive electrical networks while retaining the thermal properties of the polymer material,” says Spadaccini. “Powering micro- and nanoscale sensors for homeland security applications is a challenging problem. Many conceptual ideas have been proposed, but none has been adequately developed yet.”

Coin-Size Neutron Detector

An important homeland security effort is developing systems to detect threat sources of nuclear or radiological materials. Detectors to be used in the field have special requirements. They must operate efficiently at ambient temperature and be small enough for use in covert operations. They also must be inexpensive and robust so they can be widely deployed with minimal maintenance. Because nuclear materials emit both gamma rays and neutrons, Livermore is designing devices that can detect the signatures of both. (See the highlight on pp. 6–7.)

To meet all of these needs, engineers are modifying the detector technology currently available. For example, many gamma-ray detectors are cooled with liquid

nitrogen, which significantly increases the system’s size. Neutron detectors used in the field typically have tubes filled with helium gas. These instruments are large, require high voltage to operate, and are sensitive to vibration.

With funding from Livermore’s Laboratory Directed Research and Development (LDRD) Program, CMNT engineer Rebecca Nikolic and Tzu-Fang Wang from CMLS are using microscale materials to fabricate a high-efficiency thermal neutron detector. Thermal neutrons are more easily absorbed than high-energy neutrons, and their energy level is similar to that of molecules in a room-temperature gas. Thus, a thermal neutron detector can operate at room temperature. The challenge for Nikolic and Wang is improving the system’s efficiency.

A typical thermal neutron detector has a 50-millimeter-diameter vacuum tube filled with helium gas and operates with about 1,000 volts of power. In laboratory experiments, its detection efficiency is greater than 70 percent. Efficiency drops to about 20 percent in smaller instruments designed for field applications because adjustments are needed to make the helium-tube equipment more stable for long-term deployment.

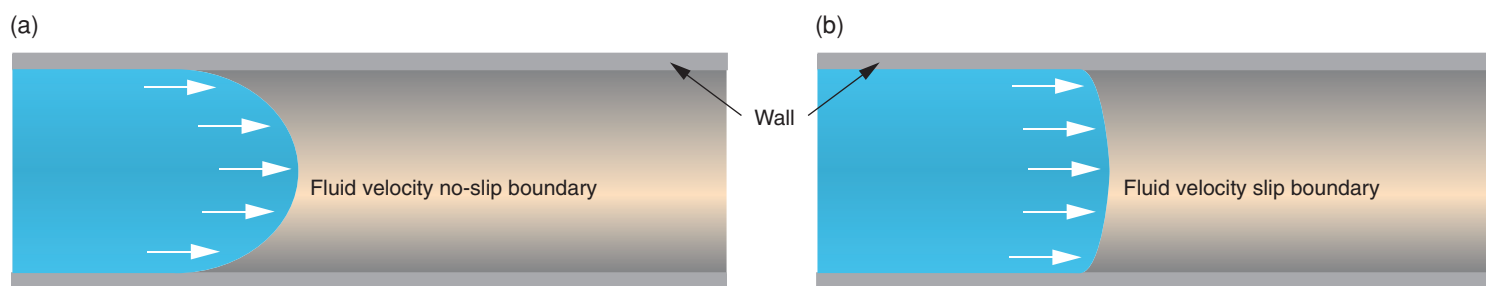
The Livermore team has designed a device called the pillar detector that offers at least twice the efficiency of conventional thermal neutron detectors used in the field. Instead of helium, the pillar detector relies on a carefully constructed platform of etched silicon pillars interspersed with boron.

Incoming neutrons interact with the boron to produce alpha particles. The alpha particles, in turn, interact with the semiconductor and create the current that provides the electronic signal.

According to Nikolic, the 3D structure of the detector maximizes the capture of neutrons. “We can adjust the pillar etch depth to provide a thicker boron layer for high neutron capture,” she says. “We can also adjust the spacing between the pillars so the alpha particles don’t have to travel far, which provides the device with high efficiency.” Project collaborators from the University of Nebraska at Lincoln are using chemical vapor deposition to apply the boron layer. The team plans to have a prototype device ready for testing at the end of this year.

Fluid Flow at the Nanoscale

Biological pathogens pose another significant threat to the nation. In the early



(a) A continuum model of fluid velocity treats particles uniformly and assumes that particles traveling near a channel wall have zero velocity, or no slip.

(b) A particle-based model can more accurately simulate micrometer-size channels because it allows particles near the wall to exhibit slip and not slow to zero velocity.

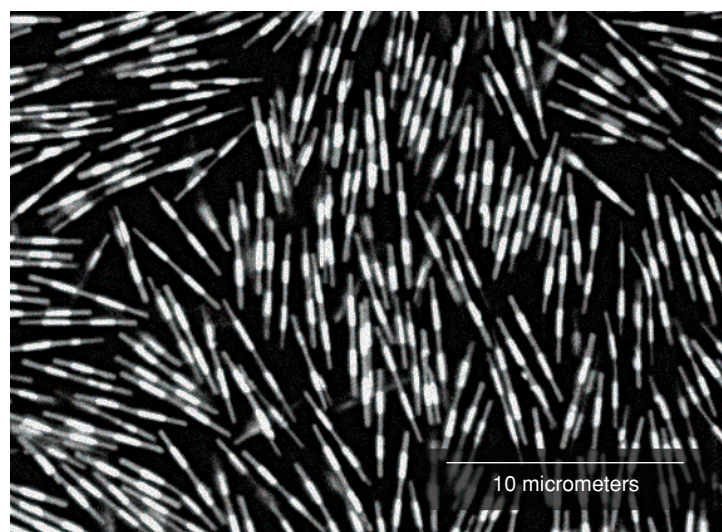
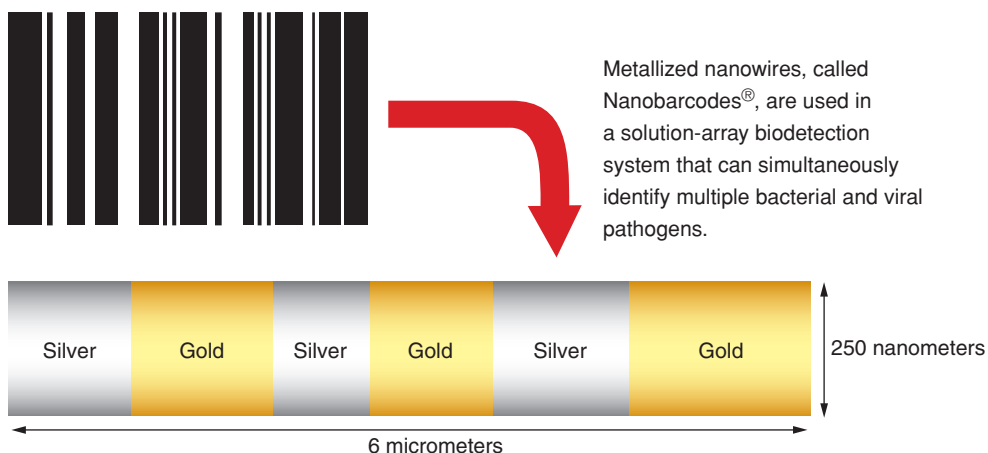
1990s, CMNT responded to this growing threat by developing microfluidic detection devices that could identify microbes. (See *S&TR*, December 2001, pp. 4–11.)

To help design the microfluidic devices, CMNT engineer Todd Weisgraber has developed new methods to simulate fluid transport in these devices. Traditional simulations of fluid flow use a continuum model. Continuum models assume that fluid properties and velocity vary independently from the movement of individual molecules. Such assumptions can distort a simulation of flow in micrometer- or nanometer-size geometries, where channels are only a few molecules wide.

“Fluid moving through very small channels can exhibit different behavior than it does in larger geometries,” says Weisgraber. For example, a gas flowing in a micrometer-size channel exhibits slip—that is, the fluid velocity at the walls of the channel does not slow to zero. In the continuum model, fluid at the wall has zero velocity, an assumption researchers refer to as the no-slip condition.

Particle-based simulations are effective at capturing noncontinuum behavior, but they require more intensive computational resources. “Instead of the particle-based approach, we’re modifying our continuum models to incorporate noncontinuum effects in a computationally efficient manner,” says Weisgraber.

In an LDRD project, Weisgraber and chemical engineer David Clague simulated gas flows in 1-micrometer-wide channels. Building on the results of their research, Weisgraber is developing a particle-based physical model called direct simulation Monte Carlo to examine flow in microchannels measuring 100 micrometers long and 1 micrometer wide. The results will help the team



In a solution-array biodetection system, bar-coded particles can be viewed using image processing software and a standard optical microscope.

improve their continuum codes to incorporate noncontinuum behavior.

Bar-Coded Particles

LDRD funded another CMNT effort led by materials scientist George Dougherty to demonstrate a solution-array biodetection system that uses bar-coded particles. The multiplexed assay builds on the particle-based solution array developed for Livermore’s Autonomous Pathogen Detection System

(APDS). (See *S&TR*, January/February 2002, pp. 24–26; October 2004, pp. 4–5.)

A major advantage of particle-based solution arrays over conventional biomarker systems that use 2D microarray chips is that they can simultaneously target multiple types of markers (DNA, RNA, or protein). And because the particles are in solution rather than fixed on a chip, they have greater interaction with potential threat agents,

allowing faster results. In the APDS array, polymer beads are coated with antibodies, and each microbead is colored according to the type of agent it detects. Dougherty and CMLS biochemist Jeff Tok used fabrication techniques developed at CMNT to combine APDS technology with Nanobarcodes[®], which are developed by the team's industrial partner, Oxonica, Inc. (formerly Nanoplex Technologies, Inc.).

Nanobarcodes are metallized nanowires approximately 250 nanometers in diameter and 6 micrometers long and composed of alternating segments of silver, gold, or other metals. Electrodepositing the metals within porous alumina templates produces striping patterns similar to the bar codes on merchandise.

Dougherty and Tok use a multistep process to fabricate the microfluidic card for the miniature system. First, a polymer layer is cast onto a patterned mold, which is then bonded to a glass substrate to form liquid microchannels. Particles in the solution are coated with a special compound to prevent them from aggregating. The molecules of this compound self-assemble and bind to the surface of the Nanobarcodes. The exposed ends of the molecules are chemically treated so that particles will

have a biochemical affinity for a specific antibody. To ensure that particles do not overlap as they flow through the device, the team devised a technique to lithographically etch parallel grooves into the surface of the glass substrate, aligning the particles for easy viewing.

Particles traveling within microscopic channels are subject to several physical forces, which researchers can exploit to move particles of interest within the channels for further study. Dougherty's team, which includes Livermore engineer Klint Rose, collaborated with professor Juan Santiago's group at Stanford University on experiments to determine optimal approaches for moving particles in the device.

The particles are examined with image processing software and a standard optical microscope. The assay panel used in developing the system includes four particle patterns, which represent possible bacterial, viral, and biotoxin threats. In a demonstration project, the system successfully detected multiple agents simultaneously.

A Road Map for Innovation

Many CMNT researchers such as Dougherty have experience in multiple disciplines. These skills are

valuable in the center's collaborative efforts, whether these are projects with colleagues at Livermore or with external partners. Krishnan notes, "One of the Laboratory's goals is to recruit experts for new science and technology areas and connect them to the ongoing programmatic work."

Part of Krishnan's responsibility as the center's director is to establish a technology road map that prioritizes future developments and factors in the cost and lead time necessary to demonstrate novel technologies. CMNT's talented staff and unique fabrication facilities promise innovative solutions to a wide range of national security problems for years to come.

—Gabriele Rennie

Key Words: Center for Micro- and Nanotechnology (CMNT), deformable mirror, grayscale lithography, microelectrode array, microelectromechanical systems (MEMS), microfluidic device, microresonator, Nanobarcodes[®], nanolaminate, photonics, pillar detector, retinal prosthesis, thermal neutron detector.

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